A Leader-Follower Algorithm for Multiple AUV Formations

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Abstract- In the future, it may be possible to employ large numbers of autonomous marine vehicles to perform tedious and dangerous tasks, such as minesweeping. Hypothetically, groups of vehicles may leverage their numbers by cooperating. A fundamental form of cooperation is to perform tasks while maintaining a geometric formation. The formation behavior can then enable other cooperative behaviors. In this paper, we describe a leader-follower formation-flying control algorithm. This algorithm can be applied to one-, two-, and three-dimensional formations, and contains a degree of built-in robustness. Simulations and experiments are described that characterize the performance of the formation control algorithm. The experiments utilized surface craft that were equipped with an acoustic navigation and communication system, representative of the technologies that constrain the operation of underwater autonomous vehicles. The simulations likewise included the discrete-time nature of the communication and navigation.

I. INTRODUCTION

Recent events have shown the value of using highly automated technology in the battlefield. Autonomous aircraft, terrestrial and marine vehicles have accomplished important missions while reducing risk to personnel. As greater numbers of autonomous vehicles are employed in the future, it is hoped that lower costs and force-multiplier benefits can also be achieved.

A task that can benefit from the use of autonomous vehicles is marine mine-sweeping. Marine mines are a low-cost and widely used technology that is very dangerous even to the most modern naval forces. Consequently, tedious and dangerous mine-sweeping activities are a necessity for many naval operations, and may become increasingly important for domestic security. Already, Autonomous Underwater Vehicles (AUVs) were used to search 3.5 million square meters of shallow water for mines in Operation Enduring Freedom in Iraq 2003 [1].

In the future, large groups of AUV's may be used to locate marine mines over wide areas. It is thought that cooperative behavior between vehicles in these large groups will leverage their numbers. Several forms of cooperative behaviors for AUV's have been proposed. These include coordinated gradient search [2] for finding underwater plumes, market-governed cooperation [3], and various forms of formation-flying [4-7].

There are reasons to believe that formation-flying cooperative behavior can increase the efficiency of group performance. Military aircraft, ground units, and naval forces use this strategy to benefit from mutual protection, concentration of offensive power, and simplification of control. It is thought that AUV's may profit from formation-flying by close proximity. For example, if a vehicle is lost during mine-sweeping, the other vehicles could quickly change formation to cover the lost vehicle's area. Also, when potential mines are identified, they could be further scrutinized by other vehicles that may have different sensors. Close proximity may be exploited to exchange data between vehicles at high speed and reduce transit times for reactive behaviors. In particular, the ability to exchange data at close proximity can help to mitigate the low bandwidth availability of the underwater communications channel.

We describe a formation-flying control algorithm for underwater autonomous vehicles. The algorithm employs a variant of the leader-follower type strategy to maintain a fixed geometrical formation while navigating mission waypoints. A leader vehicle navigates the mission waypoints using acoustic Long Base Line (LBL) measurements of position. Each follower vehicle maintains its place in formation using acoustic LBL measurements of inertial position and knowledge of the leader vehicle position. The followers obtain the position of the leader vehicle via a parallel acoustic modem broadcast. All vehicles have knowledge of the mission inertial waypoints. The use of leader position and individual vehicle position is similar to a leader-follower algorithm described in [7], except that a dead reckoning sensor is not used to determine vehicle position. Other fixed-formation leader-follower approaches [4,6], assume that only the leader vehicle has access to inertial information, and that follower vehicles communicate with their neighbors to exchange relative position data. A decentralized approach to the control of groups of vehicles [5] ensures that the vehicles in the group will be in relative proximity, but that the formation is not fixed. In this scheme, all vehicles must know their inertial position. Additionally, an "exogenous" system must know of each vehicle position, and broadcast a control signal to each vehicle derived from the vehicle position information. Although the vehicles are not required to communicate with another, they are required to communicate with the "exogenous" system.

The leader-follower algorithm described in this paper contains a degree of built-in robustness, and the only acoustic communication required is an intermittent broadcast from the leader vehicle. If the leader vehicle becomes incapacitated, the followers may complete their mission by reverting to independent navigation using inertial LBL information. Or, a follower vehicle may substitute for the leader. The algorithm may be applied to one-, two- and three-dimensional formations. Because the leader broadcasts its position to each follower in parallel, this requirement does not place an upper limit on the number of vehicles in a formation. Present acoustic LBL technology, which requires that vehicles obtain their inertial position at least in part by sequence, would place a limit on the number of vehicles in a formation.

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In this paper, we present realistic simulations and experimental data that describe the performance of our leader-follower formation-flying algorithm. Simulations and experiments are necessary because stability for leader-follower type arrangements has only been established for continuous time systems [8]. The experiments used a system developed at the Woods Hole Oceanographic Institution for underwater acoustic communication and LBL navigation [9]. This system was appropriately mounted to surface craft. The simulations were performed using the Autonomous Littoral Warfare Systems Evaluator (ALWSE), modified to incorporate vehicle dynamics. To model the discrete-time nature of the system, it was conservatively estimated that an LBL position measurement took 2 seconds per vehicle, and an acoustic message required 4 seconds plus acoustic time-of-flight. Use of the ALWSE environment provided a simulation of actual paths taken by a formation governed by a particular controller, and a means to evaluate performance in terms of area coverage or mine-like objects detected.

II. CONTROL ALGORITHM

The control system presented herein consists of both a trajectory and formation control algorithm. An autonomous vehicle needs some type of trajectory control in order to follow a prescribed path. The formation control algorithm discussed in this paper is not restricted to any particular trajectory control. The prescribed path for this paper is generated with waypoints; however, the exact method used to generate the trajectory is also unimportant. It is assumed that LBL navigation is used for the vehicle to determine its position relative to its path. A lawnmower type search pattern is used to illustrate this method.

The time required to search an area could be reduced if more than one vehicle were used. The simplest approach to utilize multiple vehicles would be to divide the search area into as many smaller areas as there are vehicles. This requires each vehicle to follow a separate path specific to their individual area.

The formation control presented in this paper assumes that each vehicle follows a specific path. The paths used in the lawnmower search pattern are generated form the path of the leader. For example, the path of each vehicle may be displaced a specified distance from the leader's desired path. Each vehicle knows the leader's waypoints and generates its desired path according to its position in the formation. In this fashion any vehicle could fill any position in the formation including the leader's position. Likewise, the leader role might be passed among the platoon if such a scheme is desired.

The formation control algorithm varies the velocity of each vehicle to maintain a specified distance from the leader. In this scheme, only the leader needs to periodically broadcast its position to the following vehicles to maintain the formation. If intercommunication is lost, the vehicles will revert to following their trajectories and searching their areas independently.

The remainder of this section describes these two controllers in more detail.

A. Trajectory control.

The trajectory control algorithm for small autonomous vehicles presented uses the perpendicular distance to the path and the heading error to control each vehicle to a desired path. Path following consists of controlling a vehicle such that it passes close to each of the waypoints in the proper order. This implies that the
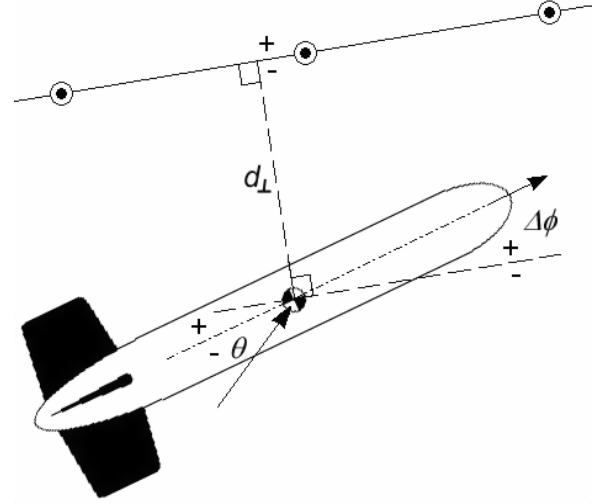

Fig. 1. Trajectory control.

vehicle attempts to be close to and parallel to its path. In Fig. 1, the trajectory control law is illustrated graphically. When the vehicle is far from the trajectory, the distance component of the controller dominates and forces the vehicle toward the trajectory. When the vehicle is close to the path, the angle component becomes more significant and forces the vehicle to head in a direction parallel to the desired path. The control law for the direction of the force, θ, is based on the perpendicular distance from the trajectory, $d_\perp$, and the difference in angle between the vehicle's heading and the angle of the desired trajectory, $\Delta\phi$. This heading control law can be written as

$$\theta = k_{d_\perp} d_\perp + k_{\Delta\phi} \Delta\phi, \tag{1}$$

where $k_{d\perp}$ and $k_{\Delta\phi}$ are the control constants to be optimized for the dynamic system.

The trajectory control algorithm also includes a velocity control component to regulate velocity to a desired value, v_{ref}. We use a traditional proportional gain controller that is linearized about the reference velocity. The magnitude of the force, $\|F\|$, is based on the difference between the reference velocity, v_{ref}, and the vehicle velocity, v, as well as a steady state force, F_{ss}, which is a function of the reference velocity. This velocity control law can be expresses as

$$\left\| \vec{F} \right\| = k_v \left(v_{ref} - v \right) + F_{ss} \left(v_{ref} \right), \tag{2}$$

where k_v is another control constant.

B. Formation control.

In the formation control algorithm, the follower vehicles need to maintain a desired distance from the leader. As a follower vehicle falls behind, the force must become larger to accelerate the vehicle closer to the leader. A one dimensional formation of this control algorithm is shown in Fig. 2. This algorithm can be implemented by making one small change to the velocity control law presented in (2). The followers must adjust their velocity to maintain the desired distance to the leader. The force magnitude, $\|F\|$, is now also related to the displacement error, $(d-d_{ref})$, and is expressed as

$$\left\| \vec{F} \right\| = k_v \left(v_{ref} - v \right) + k_d \left(d - d_{ref} \right) + F_{ss} \left(v_{ref} \right). \qquad (3)$$

Again, k_v and k_d are control constants to be optimized.

The same reference velocity is used by every vehicle in the formation so all the vehicles will try to move at the same velocity. The reference velocity may be either a constant value throughout a mission or it can be modulated as seen fit by the leader. For example, a leader may declare a slower than normal fleet velocity when the vehicles are organizing themselves before a mission, or when the leader senses that the fleet needs to reorganize itself. The leader may also set the fleet velocity to a higher than normal setting for transit to a target field or to perform an evacuation of a dangerous situation.

C. Formation Discussion

One can see in Fig. 2 that the formation control law applies directly to 1-dimensional formations where all of the vehicles share the same trajectory, and the track is relatively straight. However, this same law is flexible enough to apply to more complex 2-dimensional and 3-dimensional formations. In Fig. 3, the paths of the followers are parallel to the leader's path and offset by a desired distance, δ. This transforms the 1-dimensional formation from Fig. 2 into a 2-dimensional formation. Still, the same formation control algorithm applies. This formation law can be extended to 3-dimensions quite simply by adding a desired depth to the control laws. The vehicles then can search at different depths for different types of mines or to play different roles in the formation. If all communications between vehicles are lost, then the vehicles would revert to the case where each vehicle would follow its prescribed trajectory and search its area independently of the other vehicles.

Because the formation algorithm is flexible enough for any number of formations, switching between formations is also possible without changing the algorithm. The scalar distance between two vehicles is independent of the formation. The reference offset distance, δ, may be defined as a certain distance to the port or starboard, to create nested paths. Or it may be defined to the North, South, East, West, or in any direction to create copied paths. In Fig. 4, the offsets are defined to the West. The turn executed by the formation to the East automatically transforms the 2-dimensional formation to a 1-dimensional formation. Since the control law is flexible enough to handle both, it is able to exchange between the two easily.

One should note that some formations are more natural in certain situations than others. In Fig. 4, the vehicles are formed into a single wing platoon. This formation is very effective with copied paths where each vehicle has evenly spaced lawnmower searches. A delta formation with vehicles on either side of the leader can run into problems in a copied path formation. The mirrored pairs of the delta would attempt to occupy the same point in space when the 2-dimensional formation collapsed into 1-dimension. Delta formations work well in nested loop situations. With the formation control law presented here, vehicles in outer loops automatically increase their speed to complete the loop while vehicles on the inner loops decrease speed to maintain the formation.
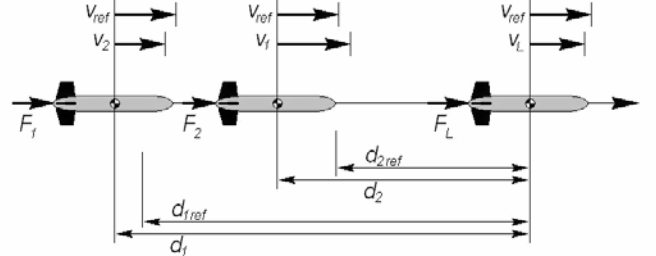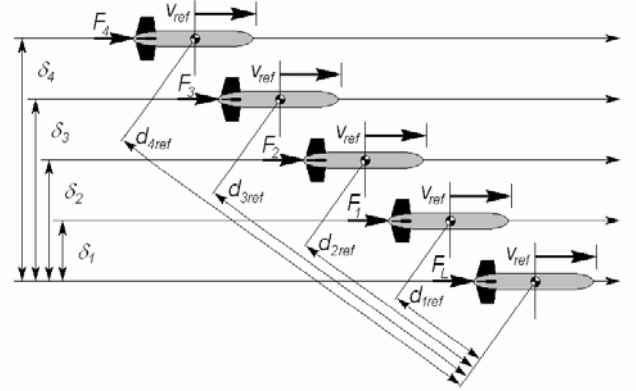

Fig. 2. Algorithm applied to 1D formation.

Fig. 3. Algorithm applied to 2D formation.

Fig. 5 shows one pattern that illustrates how this control scheme can be implemented. Previously, the only discussion about timing was to say that the leader needs to periodically broadcast its position. Because of the periodic updates from the LBL and the leader's broadcast, the system is inherently discrete. For the five vehicles shown in Fig. 5, the timing sequence is described in Table 1. To enable the system to work in this discrete manner, a predictor that estimates the location of the vehicle between LBL position updates was used. We used ALWSE-MC to perform the simulation shown in Fig. 5. This simulation uses the algorithm discussed above to perform a lawnmower search pattern for mines. The same control algorithm is used for both 1-dimensional and 2-dimensional formations in the example. When the simulation is initiated, the vehicles are placed at random near the start of the course. The vehicles form themselves into a 1-dimensional circle until all of the vehicles
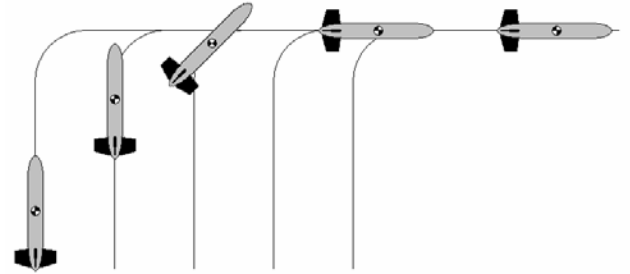

Fig. 4. Transformation from 2D to 1D formation.

are in position. The vehicles then move into their 2-D positions to begin their search. The mines that are found were circled for illustrative purposes. Notice that some mines were not found. The ALWSE-MC program is a statistical based program that can be used to simulate the natural environment with all of its uncertainties. The user can then optimize the parameters to make the fleet of vehicles perform better.

One can see that the formation algorithm presented has many desirable advantages. First, it is a simple system that has low communication requirements. The system is robust enough to tolerate loss of communication or the loss of any vehicle including the leader. It can be applied to 1-dimensional, 2-dimensional, and 3-dimensional formations. The algorithm can be expanded to control a large number of vehicles.

III. EXPERIMENTS

Two experiments were conducted: a single vehicle path following experiment and a two vehicle leader-follower formation experiment. The first was designed to test the trajectory algorithm, and the second; to test the formation algorithm.

A. Experimental Apparatus and Procedure

One goal of this project was to leverage existing equipment and facilities as much as possible. Two existing Acoustic Research Detachment (ARD) surface craft were utilized to emulate AUVs, one for the leader and one for a follower. Each boat, as shown in Fig. 6, was 24 ft long and contained the following electronics:

1. Acoustic micro-modem [9], developed by Woods Hole Oceanographic Institution (WHOI), to transmit data between vehicles and to provide long base-line (LBL) positioning information.

2. Rack-mount PC to run control software and provide operator interface.

3. GPS receiver card to provide time and position information.

4. Attitude sensor to provide heading and depth.

Each micro-modem was connected to an ITC-1032 transducer which was attached to a vertical bar and submerged 5 to 10 feet deep. Boat operators followed heading and velocity commands provided by the control algorithms. Controlling software was developed using both Labview and Matlab languages. Existing ARD transceiver buoys were adapted to emulate acoustic transponders needed for micro-modem LBL data. Tests were conducted using position input data from both GPS and acoustic LBL sources. GPS positions provided higher reliability and were used during the tests discussed below.

The Acoustic Tracking and Communications System (ATACS) on Lake Pend Oreille [10] supports broadband ranging waveforms and provides highly accurate acoustic ranging and tracking data. Six stationary transceiver buoys are located within the ATACS operation area. To support the WHOI micro-modem navigation capability, ATACS software was adapted to detect the LBL navigation pings emitted by the micro-modem and respond with necessary reply pings.
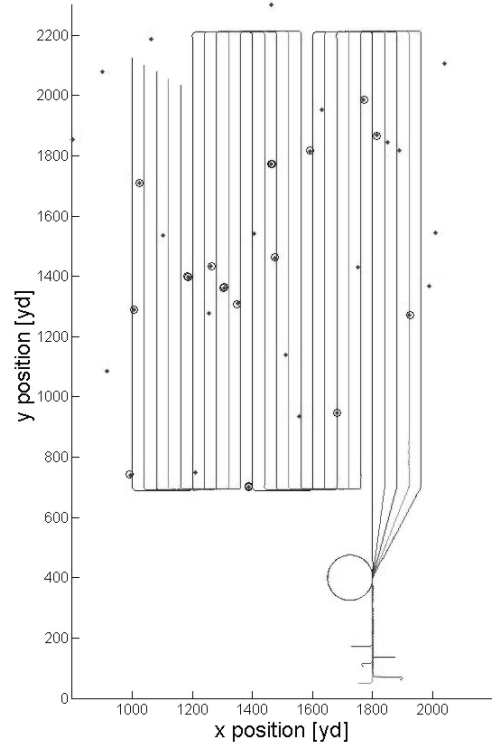

Fig. 5. ALWSE simulation of 5 vehicle performing lawnmower search in formation.

Table 1. Discrete time implementation for 5 vehicles.

Leader Acquires LBL Position	2 seconds
Leader Broadcasts Position	4 seconds
Follower 1 Acquires LBL Position	2 seconds
Follower 2 Acquires LBL Position	2 seconds
Follower 3 Acquires LBL Position	2 seconds
Follower 4 Acquires LBL Position	2 seconds
Dead Time	2 seconds
Total Time	16 second

The micro-modem then measures acoustic propagation times between vehicle and multiple transponder (transceiver) locations. Using known sound velocity, the controlling software can then compute 2-D or 3-D vehicle position using least-squares tracking algorithms.

Micro-modem navigation pings were asynchronous meaning that the precise ping emission time was unknown. Using detections at four or more ATACS transceivers, hyperbolic least-squares tracking algorithms were used to simultaneously solve for ping time and 3-D position. This technique was employed to demonstrate accurate ground-truth tracking of the WHOI micro-modem on the ATACS range.

We also attempted to measure the performance of the micro-modem LBL measurements. Although only a limited amount of data was analyzed, we were able to approximately verify the resolution of the micro-modem LBL measurements to be 100 micro-seconds, as stated by developers at WHOI.

B. Experimental Results

The single vehicle experiment tested the trajectory control algorithm. The desired boat heading calculated by the algorithm was displayed on the computer screen. The driver of the boat then matched this heading as closely as possible. The velocity control was ignored for this experiment. The driver simply operated the boat at the lowest throttle setting. Measurements of vehicle position are shown in Fig. 7. In Fig. 7, the thin line with small points describes the waypoint track. GPS position measurements are shown with open circles. The heavy broken line is the predicted position of the vehicle between GPS updates.

The two vehicle experiment tested the velocity control algorithm with one leader and one follower. The leader boat was controlled in the same manner as was the single vehicle in the previous experiment. The follower boat controlled its heading in the same manner as the previous experiment as well. However, the driver of the follower also attempted to control the velocity as calculated by the formation control algorithm. The results of this experiment are shown in Fig. 8. Two vehicles are sufficient to demonstrate feasibility of the formation because each follower only interacts with the leader, and not with other followers. This interaction only consists of the leader broadcasting its position to the followers.

The performance index for the formation control algorithm is the distance error. The distance error signal for the leader-follower experiment from the previous figure is shown in Fig. 9. One will note that since this is an error value, the graph should vary around zero. Other than the data itself, three horizontal lines also appear on the figure. The center line at about 21 is the average error. The other two lines at 7 and 35 describe the standard deviation of the error from the average.

C. Discussion of Experimental Results

One major difficulty in this experiment is the human driver completing the control loop. While driving the boat, he must decipher the numbers showing up on the computer screen into an amount to turn the wheel, and in the case of the follower vehicle, a throttle position as well. This human translation takes some time which we have not adequately integrated into the system. A fully computerized autonomous craft would be able to react quicker and have fewer errors than a human. The University of Idaho Center for Intelligent Systems Research intends to begin working with small autonomous vehicles in the near future.

The trajectories from the experiments in both Fig. 7, and Fig. 8 show promising results. The trajectories in the straight sections follow the waypoints very well. However, in both of these figures one will notice that the boats swing wide in the corners. Further simulations have demonstrated that this is caused by using a predictor that is based on an oversimplified dynamic model. A more refined dynamic model predictor of the vessels should improve the performance through the corners.

The distance error from Fig. 9 is a good indicator of the performance of the follower program. First, on average there was 21 extra feet between the leader and the follower. Most of this error could be attributed to deficiencies in the
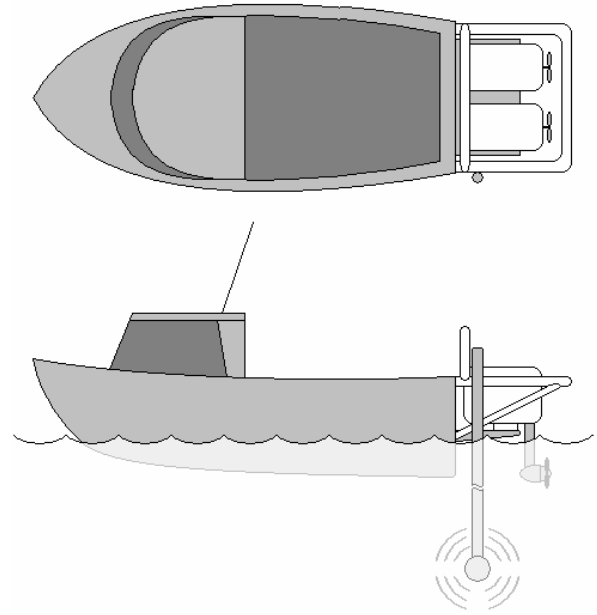

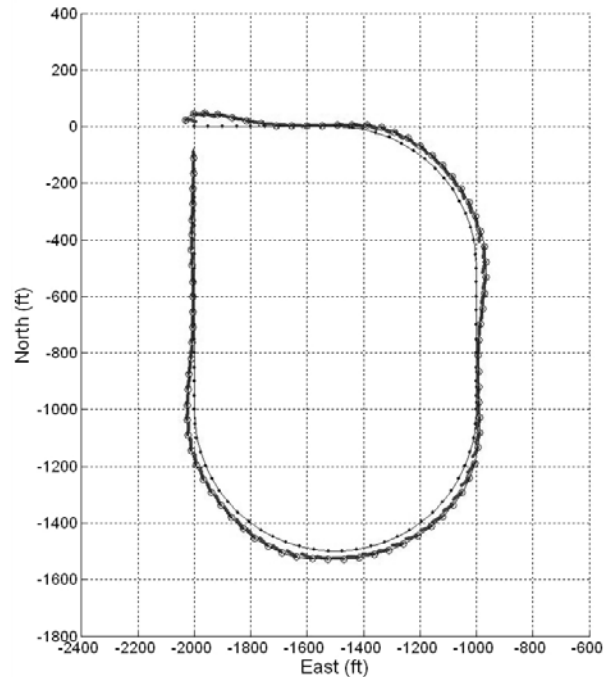Fig. 6. Surface craft used for experiments with transducer

Fig. 7. Experimentally measured leader-only poition.

controller. In the LBL timing scheme, the follower acquired its position between the leader's position acquisition and its position transmission unlike the sample timing sequence shown in Table 1. In the follower software version that was used, there was no compensation made for the possible 6 second time delay. In 6 seconds, the leader traveling at 3 feet per second can cover about 18 feet which would be added to the distance error. A more updated controller software

version is in the works to compensate for this error. Second, the distance fluctuated back and forth from -10 to +50 ft. The boat's throttle had discrete positions, not a continuum like on an automobile. The driver had to modulate through several different positions to react to the commands shown on the computer screen. Add this to the fact that a human was in control of the craft, and consider that the boat was about 30 feet long, a standard deviation in error of about 14 feet seemed reasonable.

Finally, some disruption occurred during the leader-follower test due to traffic on the lake. When testing on the ATACS range, there was very little likelihood of running into traffic, because it was several miles from the docks. However, when running the leader-follower track using GPS to simulate the LBL updates, we opted to run the tests in the bay very near the docks. While it made transit to and from the test site much quicker, we did have to yield to other boats in the bay.

IV. SUMMARY AND CONCLUSIONS

This paper presents a simple yet robust leader-follower control algorithm to control multiple autonomous vehicles. In the formation control algorithm, only the leader vehicle periodically broadcasts its position to the other vehicles that use this information to maintain a fixed distance from the leader while following a prescribed trajectory. This algorithm assumes that all the vehicles use LBL navigation to determine their position and follow a set trajectory that is derived from the leader's trajectory. The algorithm allows for the reconfiguration of the formation to compensate for the loss of any vehicle including the leader. If all communication is lost, the formation will revert to the case where the vehicles act independently to search their prescribed areas. The algorithm can be expanded to include a large number of vehicles in the formation because the leader alone communicates its position. However, the requirement that each vehicle acquires its position acoustically via an LBL navigation system does limit the maximum number of vehicles in a formation.

The algorithm is valid for controlling a formation of vehicles in one, two, or three dimensions, without any change in the control law. This property of the algorithm was demonstrated in an ALWSE-MC simulation where five vehicles used a lawnmower pattern to search for mines. The simulation showed a 1-dimensional formation circle which progressed to a 2-dimensional formation for the mine search then regressed to a 1-dimensional formation for making turns. The simulation illustrated the discrete nature of the practical implementation of the control algorithm as a sixteen second timing cycle was used in the experiment to test the algorithm. Two experimental tests were performed. The first test investigated the trajectory control algorithm and the second test investigated the formation control algorithm. It is important to note that the formation control algorithm is independent of the type of trajectory control algorithm. The experiments show that the algorithm in this paper indeed can control two vehicles in formation even with an inadequate dynamic model, and a human boat operator. Experimental results should improve with the implementation of a more sophisticated controller that includes a better predictor and accounts for delays in the discrete timing loop. We expect
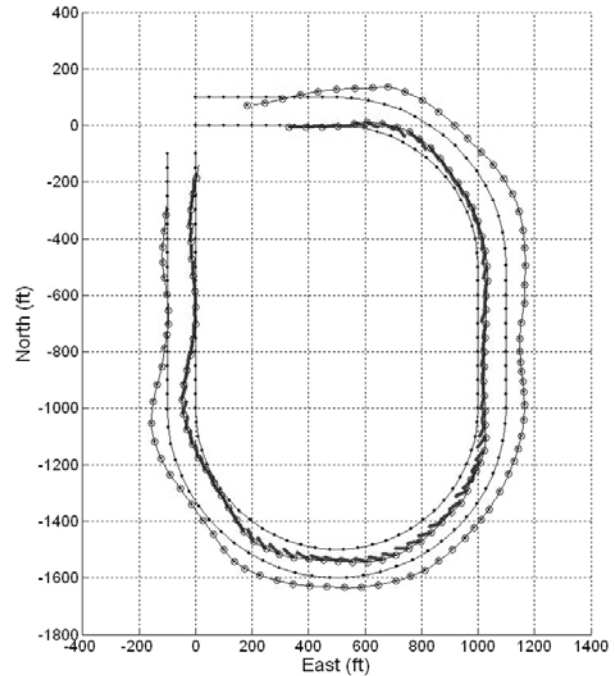

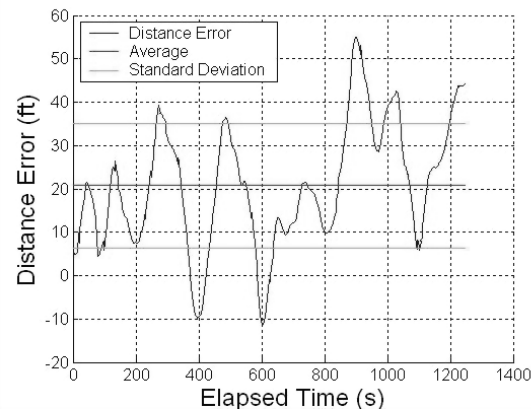Fig. 8. Experimentally measured leader-follower position.

Fig. 9. Formation position error.

that fully autonomous vehicles implementing this updated controller will perform very well.

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